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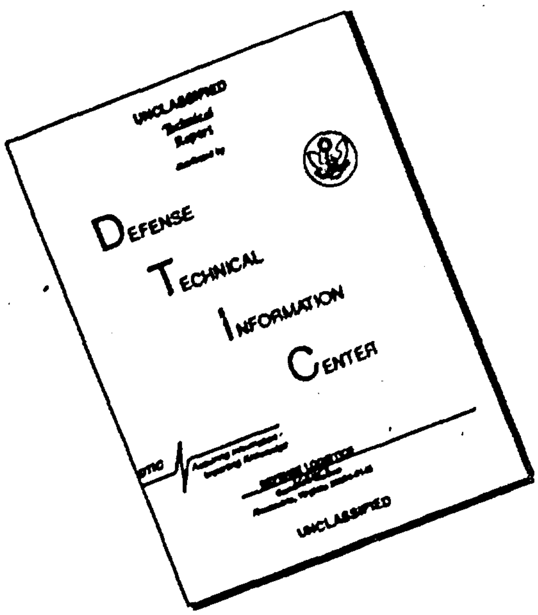

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ESL-TM-117

MEASUREMENTS OF SHOT NOISE IN TUNNEL DIODES AT LOW FORWARD VOLTAGES

by

Carl N. Berglund

August 1961

Contract No. AF-33(616)-5489 Task No. 50688

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ABSTRACT

An accurate method for experimentally determining the equivalent shunt noise-current generator in tunnel diodes in the low positive-resistance regions is described. Using this method, shot-noise measurements were made on a Type 1N2939 tunnel diode in the bias range from zero voltage to the peak point, and at three temperatures (203K 300K, and 373K). The results are presented and compared with calculated noise values. Excellent agreement obtained suggests that the existing theory of shot-noise in tunnel diodes in the low-bias region is adequate.

ACKNOWLEDGEMENT

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MEASUREMENTS OF SHOT-NOISE IN TUNNEL DIODES AT LOW FORWARD VOLTAGES

A. INTRODUCTION

In recent experimental study of noise in tunnel diodes,[1] shot and 1/f noise were measured over a wide range of bias voltage. In the negative-resistance region of the diode characteristic the shot-noise measurements agreed completely with previous theoretical and experimental results;[2] that is, the tunnel diode was found to produce the full shot noise associated with the direct current. In the positive-resistance region near the origin, high accuracy in the shot-noise measurements is difficult to achieve because of the low dynamic resistance of the diode. Since the simple relation of shot noise to direct current is not valid at voltages below the peak point, but a method of calculating the equivalent noise current from the direct current has been suggested,[3] it is of interest to obtain accurate measurements of shot noise in this bias region. It is the purpose of this memorandum to describe an accurate method of measuring tunnel-diode noise in regions of low positive resistance, and to compare, for a diode sample at various temperatures and bias voltages in the range from zero to the peak point, measured shot noise with shot noise calculated by the suggested method.

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[1] Berglund, C. N., "An Experimental Investigation of Noise in Tunnel Diodes," (Report ESL-R-114, Electronic Systems Lab., M. I. T., July 1961); also Master of Science Thesis of the same title, M. I. T. Department of Electrical Engineering, August 1961.

[2] Tiemann, J. J., "Shot Noise in Tunnel Diode Amplifiers," Proc. IRE, Vol. 48, No. 8 (August 1960), pp. 1418-1423.

[3] Pucel, R. A., "The Equivalent Noise Current of Esaki Diodes," Proc. IRE, Vol. 49, (June 1961), pp. 1080-1081.

B. THEORETICAL SHOT-NOISE

In the negative-resistance region it has been shown[1] that the tunnel diode produces full shot noise; that is, the diode may be considered shunted by a noise-current source of mean-square value

$$\overline{i_d^2} = 2qI_{eq}\Delta f \qquad (1)$$

where q is the magnitude of the charge in an electron, Δf is the bandwidth within which $\overline{i_d^2}$ is measured, and I_{eq}, the equivalent shot-noise current, is equal to the direct current I. At voltages below those associated with the negative-resistance region, it is believed that the direct current is made up chiefly of two components, the forward-directed Esaki current I_E and the reverse-directed Zener current I_Z, both of which produce full, uncorrelated shot-noise. Thus, the direct current I is

$$I = I_E - I_Z \qquad (2)$$

and the equivalent shot-noise current I_{eq} in Eq. 1 is

$$I_{eq} = I_E + I_Z \qquad (3)$$

Pucel[2] has shown that

$$I_Z = I_E\, e^{-\frac{qV}{kT_d}} \qquad (4)$$

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[1] Berglund, C. N., ESL-R-114; Tiemann, "Shot Noise."

[2] Pucel, "Equivalent Noise Current."

where k is Boltzmann's constant, T_d is the diode absolute temperature, and V is the bias voltage. From Eqs. 2, 3, and 4

$$I_{eq} = I \coth \frac{qV}{2kT_d} . \tag{5}$$

For large V, as in the negative-resistance region, coth $qV/2kT_d$ approaches unity, and the equivalent shot-noise current is approximately equal to the direct current at the bias point.

C. METHOD OF MEASUREMENT

The circuit for the noise measurements is shown in Fig. 1. To measure noise at a desired bias point, connect the signal generator to the circuit. Set the signal-generator output to some convenient level

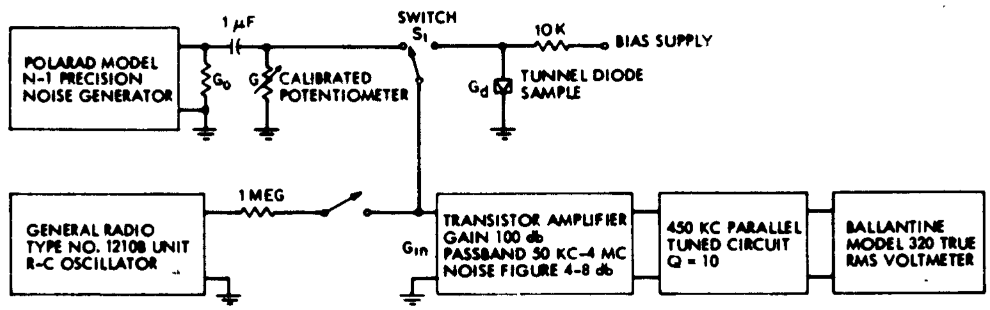

Fig. 1 Circuit for Tunnel-Diode Shot-Noise Measurements

well above the noise, but not so high that the diode operating region is nonlinear. Adjust potentiometer G to a value G_1 for which the reading on the true-rms voltmeter is the same for either position of the switch S_1.

Disconnect the signal generator and set the noise-generator output dial to a noise figure F such that the noise voltage indicated on the voltmeter is the same for either position of S_1. From the values of G_0 (the internal conductance of the noise generator), F, and G_1, the equivalent shot-noise current I_{eq} for the frequency, temperature, and bias of the measurement can be calculated as follows:

Consider the equivalent circuit of Fig. 2, where G_{in} is the input conductance of the low-noise amplifier, G_d is the dynamic conductance of the tunnel diode at the bias point, and the various noise components are

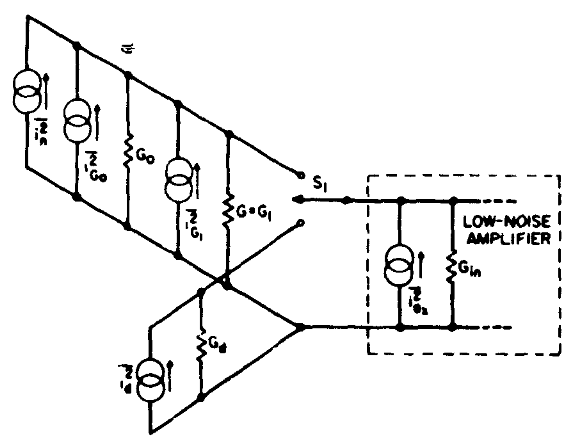

Fig. 2 Noise Equivalent Circuit for the Measurements

represented by shunt current generators labeled with their mean-square current values in a frequency band Δf -- $\overline{i_d^2}$ pertains to the tunnel diode, $\overline{i_{G_1}^{\ 2}}$ and $\overline{i_{G_0}^{\ 2}}$ represent thermal noise associated with G_1 and G_0 respectively, $\overline{i_n^2}$ is the mean-square current added by the Polarad noise generator, and $\overline{i_{ex}^2}$ denotes the equivalent input noise current of the amplifier. The method of setting G_1 assures that $\overline{i_{ex}^2}$ is the same for both positions of S_1. Since the total noise current for either position of S_1 is the same, the following equation can be written

$$\overline{i_{ex}^2} + \overline{i_d^2} = \overline{i_{G_1}^2} + \overline{i_{G_0}^2} + \overline{i_{ex}^2} + \overline{i_n^2} \tag{6}$$

Hence

$$\overline{i_d^2} = \overline{i_{G_1}^2} + \overline{i_{G_0}^2} + \overline{i_n^2} \tag{7}$$

The Polarad noise generator is calibrated to read noise figure directly in decibels, under the assumption that G_0 is at a temperature of 290 K. To relate $\overline{i_n^2}$ to the dial setting F, consider the method employed to measure amplifier noise figure. Amplifier noise-power output is measured with the noise generator connected but turned off. The noise generator is turned on and F is adjusted until the amplifier noise-power output is double the previous value. The value of F thus determined is taken to be the amplifier noise figure. Therefore, at a setting F, $\overline{i_n^2}$ is given by:

$$\overline{i_n^2} = F\, \overline{i_{G_0}^2}\, \frac{290}{T} \tag{8}$$

where T is the absolute temperature of G_0. If T is also the temperature of G_1,

$$\overline{i_{G_0}^2} = 4kTG_0\Delta f \tag{9}$$

and

$$\overline{i_{G_1}^2} = 4kTG_1\Delta f \tag{10}$$

Equations 1, 7, 8, 9, and 10 can be combined to give

$$I_{eq} = \frac{2kT}{q}(G_1 + G_0) + \frac{2k(290)}{q} G_0 F \tag{11}$$

or if $T = 290$ K,

$$I_{eq} = 50G_1 + 50G_0(F + 1) \text{ ma} \tag{12}$$

At low tunnel diode temperatures, it may be necessary to connect the noise generator across the tunnel diode instead of across G_1. The method of measurement then remains the same, but Eq. 12 is replaced by

$$I_{eq} = 50G_1 - 50G_0(F + 1) \text{ ma} \quad (T = 290\text{K}) \tag{13}$$

The accuracy of this method of noise measurement depends on the noise figure of the amplifier used. As low a noise figure as possible for the range of terminating impedances used in the measurements is desired. Small amplifier nonlinearities and errors in the voltmeter calibration do not affect the accuracy.

D. MEASUREMENTS MADE

The equivalent shot noise current of a General Electric 1-ma (peak current) germanium tunnel diode Type 1N2939 was measured at 450 kc, at three temperature (203K, 300K, and 373K), and at five-millivolt intervals of bias voltage from zero to the peak-current point. The frequency of 450 kc is high enough to assure that 1/f noise is negligible,[1] yet low enough to lie within the range of available measuring equipment and to assume negligible admittances of the diode and connecting coaxial cable capacitances. The temperature of 203K was maintained by placing the diode in a mixture of alcohol and crushed dry ice, the 300K temperature was room temperature, and the 373K measurements were made with the diode in a temperature-controlled oven. The low-noise amplifier

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[1] Berglund, ESL-R-114

(see Fig. 1) had a noise figure between 4 and 8 db for terminating impedances used in the measurements.

The measured values of equivalent noise current are indicated by circles in Fig. 3. The solid line represents calculated values, obtained by means of Eq. 5.

E. DISCUSSION OF RESULTS

The close agreement between calculated and measured values in Fig. 3 suggests that the existing theory of shot noise in the bias range from zero voltage to the peak-point voltage is adequate. For the negative-resistance region, adequacy of the theory has been shown previously.

Because 1/f noise in tunnel diodes is very large at high bias voltages, accurate measurements of shot noise at voltages beyond the valley voltage can be made only at very high frequencies. Since noise measurements at such frequencies present formidable practical problems, and because it is unlikely that high-frequency tunnel-diode circuits will be built that use the tunnel-diode characteristic much beyond the valley point, no measurements were made in this bias region.

The method of noise measurement used in this investigation has the advantage of minimizing the effect of inaccuracies in the equipment. When a low-noise amplifier is used, the error in I_{eq} becomes almost entirely dependent on the accuracy of the noise generator and the precision with which the voltmeter scale can be read. The method has the additional advantages of being rapid and simple.

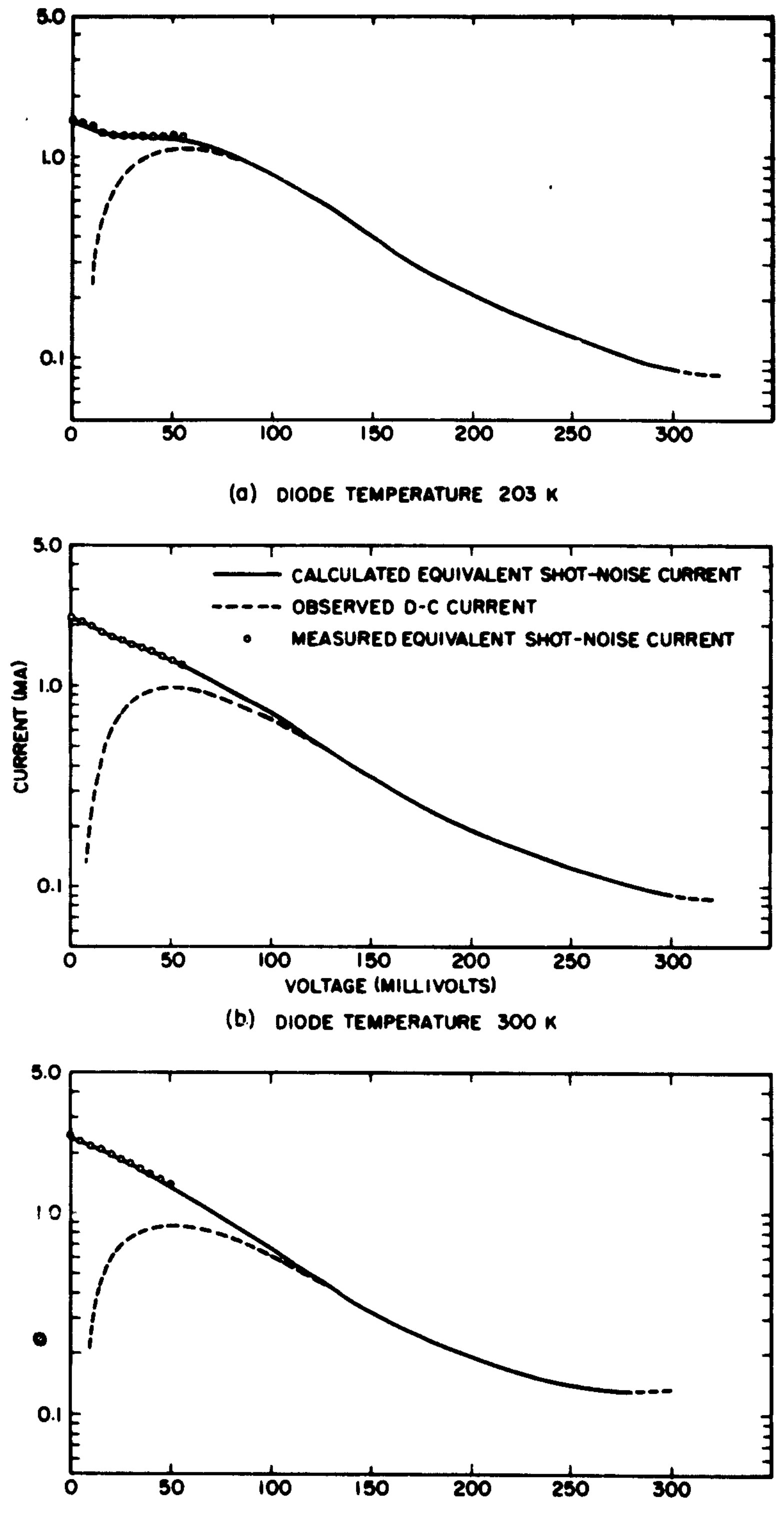

Fig. 3 Comparison of Measured and Calculated Shot-Noise in a 1-ma Germanium Tunnel Diode Type 1N2939

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Frequency-independent noise was measured at 30 Mc at room temperature. It was found that the equivalent shot-noise current of a tunnel diode at voltages above the peak-point voltage is given very closely by the observed direct current. From zero voltage to the peak-point voltage, the equivalent shot-noise current of a tunnel diode is approximated by the sum of the magnitudes of the Esaki and Zener currents.

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